Results of Ten Years of Cloud Seeding in Santa Clara County, California

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ABSTRACT

Ten seasons of commercial cloud seeding in Santa Clara County, California, are evaluated using target and control stations selected in 1955. Comparison of the linear regressions of target rainfall upon control rainfall, using seasonal totals, for the seeded winters and for ten immediately preceding ones gives evidence for a net increase in target precipitation. Examination of the rainfall distribution within the target area, which was not a part of the original evaluation plan, shows that seeding effects are concentrated downwind of the highest part of the Santa Cruz Mountains, which form the southwestern boundary of the target area, and suggests that they are limited to periods of convective instability.

1. The project

Over the past 35 years, the people of Santa Clara County, Calif., have developed a unique system of water storage based upon the extensive aquifers which underlie much of the county. Rainwater from winter storms is stored temporarily in reservoirs for later passage through percolation beds to the aquifers, where it is immune to evaporative losses.

Some cloud seeding to increase runoff into reservoirs in the county was carried out during the winter of 1951–52. The program was resumed in the fall of 1954 and has been continued each year since that time.

The target area is shown in Fig. 1. It amounts to 710 mi^2, encompassing the agricultural land on the floor of the Santa Clara Valley and the areas draining into the reservoirs in the foothills along both sides of the valley. The Santa Cruz Mountains, which form the southwestern boundary of the target area, have a maximum elevation near 3800 ft. The elevation decreases rapidly to approximately 150 ft in the Santa Clara Valley and then increases, but more gradually, as one enters the foothills of the Diablo Range. Mt. Hamilton, on the northern edge of the target area and well known as the site of the Lick Observatory, rises to approximately 4200 ft.

Substantial rainfall in Santa Clara County is nearly always associated with a large-amplitude long-wave trough off the West Coast. A recent study in objective climatology has shown that rainfall in northern California is more closely related to 700-mb flow patterns than is rainfall in other parts of the United States (Klein *et al.*, 1965). The correlation between rainfall occurrence in northern California and the height of the 700-mb surface reaches a negative extremum some 300 miles west of the Oregon coast. This implies a prevalent southwesterly flow over northern California during rainy periods. Jet streams are frequently observed, sometimes as low as 15,000 ft. The freezing level is typically between 6000 and 10,000 ft.

The approach of a major storm system to the Santa Clara Valley is ordinarily accompanied by thickening and lowering cirrus and altocumulus clouds and a development of stratus and, later, stratocumulus clouds along the coast and extending inland over the Santa Cruz Mountains. The low clouds form in the marine layer, which is capped by dry, stable air. Developments are similar to those described by Elliott (1960) in Santa Barbara County, some 200 miles further south. Light rain and drizzle frequently fall from the stratocumulus clouds even though their tops are typically only 5000 to 8000 ft above sea level and warmer than 0C.

With the closer approach of the storm, the marine layer deepens, permitting the stratocumulus clouds to thicken, and the base of the middle cloud lowers until the cloud layers merge. This merging is frequently accompanied by, or perhaps accomplished by, the outbreak of strong convection within the lower cloud deck.

A rainy period in northern California associated with a major long-wave trough can last for a week or more. However, most of the precipitation falls in one or more bursts associated with short waves embedded in the southwesterly flow. Quite often, the short waves are associated with closed low-pressure centers at the surface, which move northeastward to cross the coast near the California-Oregon border. These systems are accompanied by surface troughs with winds in Santa Clara County shifting from southeasterly to westerly at the trough passages. There is a tendency for these wind shifts to be described as frontal passages, but in

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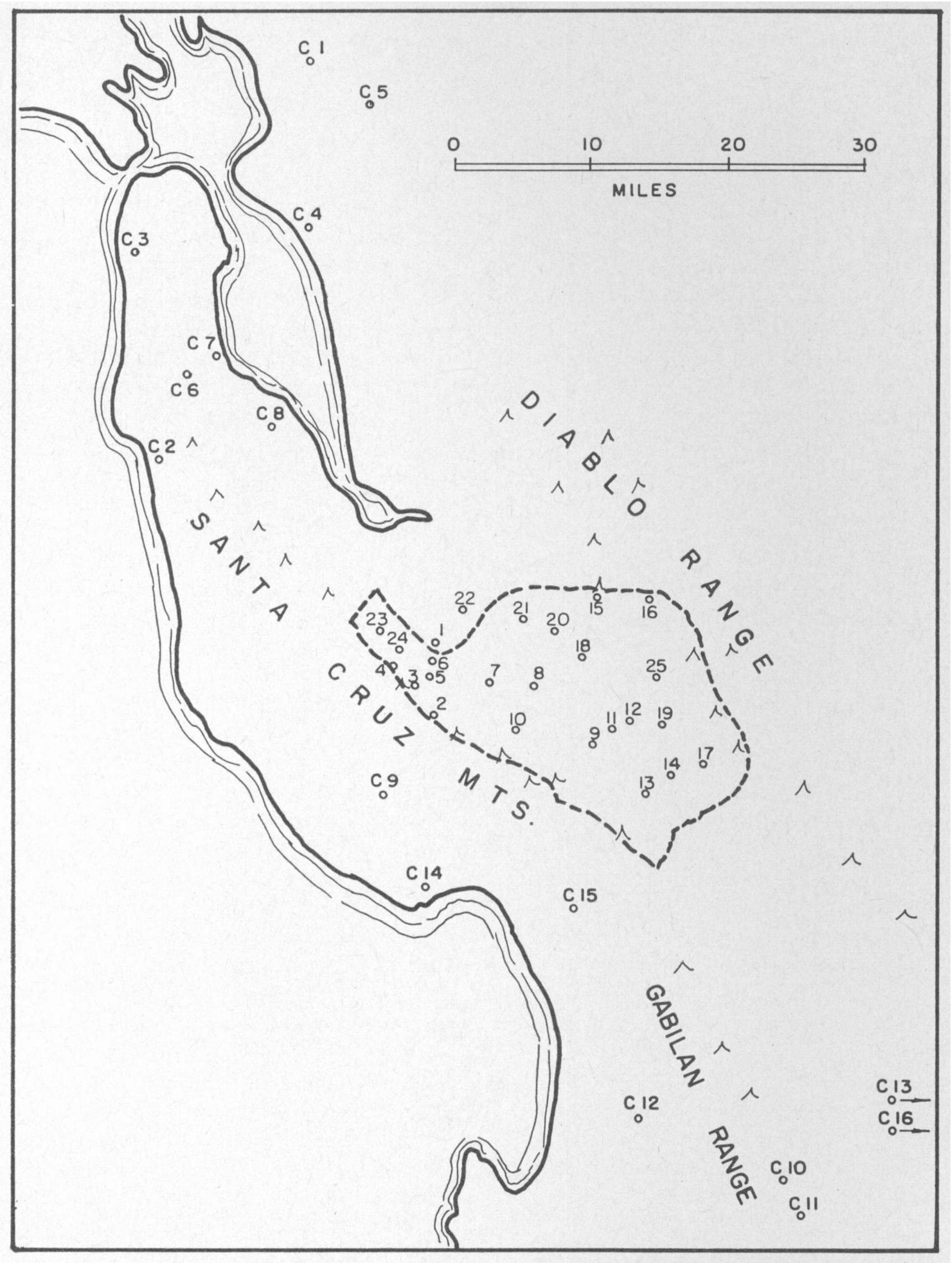

Fig. 1. Map showing target area and rainfall stations.

many cases the available radiosonde data fail to show the sloping three-dimensional structure of a true front.

There is a definite mesoscale structure within the rain areas associated with the passage of the short-wave troughs. The heaviest precipitation tends to occur in bands separated by 2–4 hours, while radar shows each band to consist of masses of irregularly spaced, intense precipitation cells. Pilots of seeding aircraft ordinarily report small hail rather than snow above the freezing level in the cells, and up-drafts speeds up to 5 m sec^{-1}.

The differences in elevation through the target area lead to pronounced differences in normal rainfall cumulations. The largest seasonal (December–March) normal for any of the target or control stations, 35 inches, occurs at Ben Lomond in the Santa Cruz Mountains. As one proceeds northeastward, the normal rainfall apparently starts to diminish before the crest of the Santa Cruz Mountains is reached [compare Bergeron (1949)]. Descending to the floor of the Santa Clara Valley, one finds normals near 8 inches at San Jose and 11 inches in the region just east of Morgan

Hill. They remain relatively small in the eastern foothills but increase again at higher elevations in the Diablo Range.

All operations to the spring of 1965, with the exception of the 1956–57 season, were conducted by one firm, the Weather Modification Company, using the same seeding techniques. Operations were directed from a field office equipped with a circuit-C teletype drop and a weather radar.

The method of operation was based on the assumption seeding could increase rainfall but not initiate it. Generators were operated with the intent of affecting those parts of the target area where precipitation cells were already present. No attempt was made to modify the fine rain falling from clouds in the marine layer ahead of major storms, which was attributed to a coalescence process.

Some seeding was done from aircraft, but the backbone of the seeding effort was a network of silver iodide generators operated on the ground. Because of the prevalence of southwesterly winds aloft during stormy periods, most of the seeding was done in the Santa Cruz Mountains.

The ground-based generators burned a solution of silver iodide and sodium iodide in acetone in a propane flame. A typical consumption rate of silver iodide was 25 gm hr^{-1} per generator with about ten generators in operation. Up to 1960, a propane-acetone generator was used on the aircraft also, but with a consumption rate of approximately 75 gm hr^{-1}. After 1960, flares containing silver iodide were used on the aircraft. Records on all generator operations and all aircraft flights were maintained by the operator and filed with the California Department of Water Resources as required by law. However, no calibrations were made of the output of the seeding devices, so it is impossible to say what concentrations of ice nuclei were achieved by the seeding operations.

The long period of operations without any basic change in seeding methods and an absence of other cloud-seeding programs near the target area render the Santa Clara Project almost unique for evaluation purposes.

2. Target-control regression analyses

The requirement that the rainfall stations used in evaluating a program be selected before the seeding is done has been noted by Court (1960).

Personnel of the operating firm met with an evaluation committee representing the County of Santa Clara in the fall of 1955 to devise a method of evaluation.[2] (Prophet, 1957). Twenty-five target stations and 18 control stations were selected. No control stations were selected to the northeast of the target area because of the prevalence of southwest winds aloft during rainy periods. It was agreed that the base period used in establishing normals for these stations would include rainfall between 1 December and 31 March for each of ten seasons ending 31 March 1954.[3] Because the target stations were not distributed uniformly within the target area, the Thiessen (1911) method was adopted for estimating the target rainfall. A simple average of rainfall amounts at the control stations was considered acceptable as a control figure.

It was agreed that the total rainfall in the target and control areas during the contract period for any particular year would be used in estimating increases due to seeding. This decision, while leading to some dilution of results by including storms not considered suitable for seeding by the operator, appears sound, as it eliminates possible bias introduced in the selection of storms for seeding (Court, 1960; Brownlee, 1960). In the present paper, all rainfall from 1 December to 31 March has been included, despite the facts that seeding ordinarily ended on 15 March and that seeding was sometimes suspended or curtailed during wet periods to avoid possible flood damage. This has been done to eliminate any possibility of bias introduced by changes in the target-control relationship from month to month.

In preparing this paper, 16 of the 18 control stations selected in 1955 have been used. Their names are shown in Table 1, and their locations (by number) in Fig. 1. One control station (San Francisco Water Department No. 101) was discontinued in 1960, while another (Buena Vista) has been dropped because of numerous gaps in its record. Some small gaps in the records for the control stations retained have been filled by assigning to the missing station the percentage of its normal seasonal rainfall found by summing the rainfall at the other controls and comparing with the sum of their seasonal normals.

All of the 25 targets stations selected in 1955 are used in the first analysis presented here. They are listed in Table 1 and located (by number) in Fig. 1. Missing data, in one case amounting to a whole station year, have been filled in by interpolating on the basis of the percentages of normal received at nearby stations. This procedure is roughly equivalent to dropping stations with missing data and realigning the boundaries of the Thiessen areas of the nearby stations. Details on all interpolations are contained in records of the Santa Clara Valley Water Conservation District.

The control precipitation and the target precipitation, the latter computed by the Thiessen method, are shown for the ten seasons of the base period and for the ten seasons seeded by the Weather Modification Company since 1954 in the second and third columns

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[2] Prophet, D. T., 1957: Some notes on the results of cloud seeding in Santa Clara County, California. Presented at 158th National Meeting of Amer. Meteor. Soc., Monterey, Calif.

[3] The "1954" season will be understood to mean the 4-month period ending 31 March 1954, and so on.

Table 1. Rainfall stations used in regression analysis.

Controls	Targets
1. Berkeley	1. Seven Mile Reservoir
2. Halfmoon Bay	2. Lake Elsman
3. Lake Merced	3. Lake Kittridge
4. Oakland Airport	4. Lake McKenzie
5. St. Mary's College	5. Montevina
6. San Andreas Lake	6. Los Gatos Reservoir
7. San Francisco Airport	7. Guadalupe Reservoir
8. San Mateo	8. Almaden Reservoir
9. Ben Lomond	9. Morgan Hill 3 SW
10. Gonzalez 9 ENE	10. Morgan Hill 6 WNW*
11. Pinnacles	11. Morgan Hill SCS
12. Salinas Airport	12. Morgan Hill 2E
13. San Benito	13. Gilroy
14. Santa Cruz	14. Gilroy 5E
15. Watsonville	15. Mt. Hamilton
16. Upper Tres Pinos	16. San Francisco Water Dept. No. 109
	17. Gilroy 8NE
	18. Coon Hollow
	19. Coyote Reservoir
	20. Evergreen (Kuhn)
	21. Evergreen (Mirassou)
	22. San Jose
	23. Stevens Creek
	24. Big Basin Way
	25. Morgan Hill 10E

* Formerly Morgan Hill (Bossana).

Table 2. Target and control rainfall by seasons.

Season (4 months ending 31 March)	Control rainfall	Target rainfall (Thiessen method 25 gauges)	Target rainfall (no Thiessen method 22 gauges)
		Base period	
1945	13.95	15.76	16.34
1946	14.08	14.72	15.50
1947	8.42	8.83	9.29
1948	8.18	7.93	8.20
1949	16.71	17.48	19.17
1950	15.87	12.57	13.34
1951	14.01	13.99	14.65
1952	27.76	28.01	30.69
1953	15.05	15.47	17.22
1954	12.51	13.50	15.17
		Seeded period	
1955	11.84	12.70	13.80
1956	25.15	29.75	32.96
1957 (see text)	—	—	—
1958	26.68	29.01	31.73
1959	12.98	16.72	18.20
1960	12.67	12.88	13.67
1961	8.35	7.44	8.13
1962	17.03	18.34	20.17
1963	15.55	20.20	22.14
1964	7.88	7.54	8.03
1965	15.13	17.34	19.23

of Table 2. No transformations have been applied to normalize the data because of possible bias in the interpretation of results based on transformed data (Neyman and Scott, 1961). The regression techniques used are applicable to non-normal populations.

In an earlier paper on the Santa Clara Project (Dennis, 1960), a regression line was drawn for the base period and the departures for three seeded years were tested assuming a Student's *t* distribution (Thom, 1957). Now that the numbers of seeded and unseeded years are nearly equal, it appears more satisfactory to determine regression lines for both the seeded and unseeded years and test these lines for coincidence (Brownlee, 1960). This procedure has the advantage of being able to detect such hypothetical seeding effects as increases in dry years and decreases in wet years, or vice versa, as well as systematic increases or decreases due to seeding. This has been done following the methods for analysis of covariance given by Dixon and Massey (1957).

The data given in columns 2 and 3 of Table 2 are shown on a scatter diagram in Fig. 2. The test of the hypothesis that the target means during the two groups of years are the same when adjusted for the difference in control means yields a value of 5.0 for *F*. If we were dealing with normal distributions, an *F* of

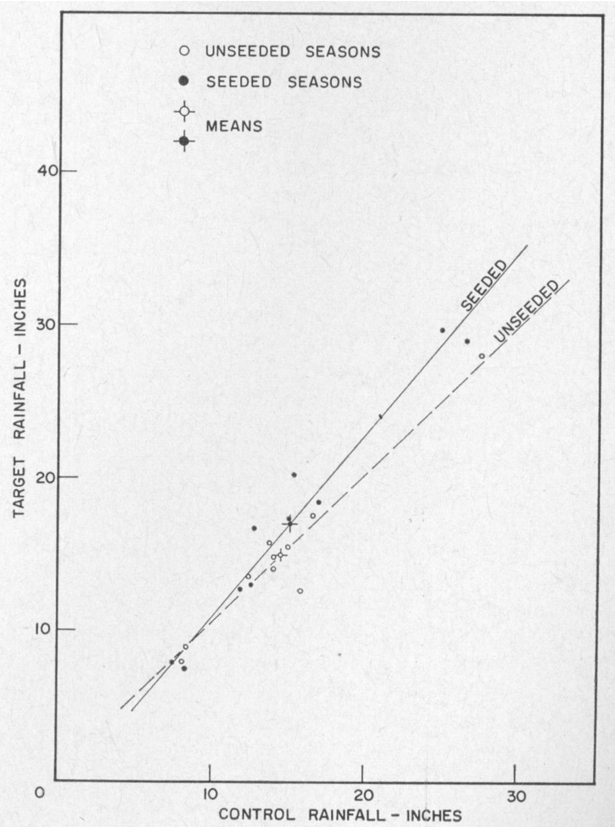

Fig. 2. Scatter diagram showing target and control rainfall during base period and during ten seeded seasons.

approximately 3.6 would be required for rejection of the hypothesis at the 5 per cent significance level. Because the data are not normal, we cannot specify exactly the significance level at which one can reject the null hypothesis, but we can say that it is very unlikely that the adjusted target means are the same. A test of the hypothesis that one regression line can be used for both sets of plotted points yields an F of 4.1. As the adjusted target means for the seeded and unseeded periods are different, it is not surprising that one regression line can not be used for the two groups of data. A test of the hypothesis that the slopes of the two regression lines are the same yields an F of 2.6, so we do not reject that possibility, even though the computed slopes are quite different (1.0 for the base period, 1.2 for the seeded period).

In the above analysis, 1952 has been included among the unseeded seasons even though, as noted above, some seeding was conducted. The original decision to count 1952 in the base period appears wrong to the present authors, although its inclusion could never lead one to ascribe positive effects to seeding if none were present. One could also object to the inclusion of 1955 among the seeded seasons, because the target and control stations were selected after that winter's operations were finished. Accordingly, a second regression analysis has been made to compare the nine years of seeding by Weather Modification Company since 1955 with the nine completely unseeded years during the base period. As it turns out, the results are similar to those obtained in the first analysis but somewhat more decisive (See Table 3).

Several persons have suggested that apparent increases in precipitation on the Santa Clara Project could have been due to the slight changes in the contract period from year to year, or to the use of the Thiessen method, or to the way missing data had been filled in. The first of these technicalities has been overcome in the analyses just given. As a check on the other points, target-control relationships have been computed without the Thiessen method, which also allows us to abandon the target stations with the most serious breaks in their records. Three stations, Morgan Hill 6 WNW, Mt. Hamilton, and Coon Hollow have been dropped. The target rainfall for each of the twenty seasons under consideration obtained by averaging the seasonal totals at the 22 remaining stations is shown in the last column of Table 2. These averages have been compared with the control rainfall for both the 10 years-versus-10 years and the 9 years-versus-9 years cases. The results of all the analyses are summarized in Table 3.

Table 3 shows that the results of the regression analysis, involving 3200 station-months of records, are insensitive to the inclusion of some interpolated data and to the details of the computational methods. We conclude that the target-control relationship really did shift in favor of the target at the time cloud seeding was undertaken in Santa Clara County and that the change has persisted ever since.

TABLE 3. Values of F.

	Thiessen method		No Thiessen method	
Hypothesis	10 years vs. 10 years	9 years vs. 9 years	10 years vs. 10 years	9 years vs. 9 years
Adjusted means the same	5.0	10.6	5.9	3.9
One regression line	3.6	6.0	4.5	2.7
Slopes the same	2.6	1.3	2.6	1.4

3. Rainfall distributions and atmospheric instability

The possibility that a change in a target-control regression could occur naturally has been mentioned in several papers on cloud-seeding evaluation. Godson (1955), in examining a project in Manitoba and Saskatchewan, established a regression line using only part of the record available for unseeded years and compared unseeded as well as seeded years to the regression line. However, as Neyman and Scott (1961) have already pointed out, this procedure cannot lead to any positive conclusions; absence of a natural change in the target-control relationship in 1944 may suggest, but cannot guarantee, absence of a natural change in 1954.

Some light can be shed on the subject by an examination of rainfall distributions within the target area. In an evaluation of the 1956 operations, Prophet (*loc. cit.*) drew attention to the fact that the precipitation in the target area during seeded storms was not at all uniform, even when the amounts were expressed as percentages of the averages over the 10-yr base period. As early as 1958, it was apparent that those storms in which the overall target-control relationship was most favorable were characterized by a distinct rainfall distribution in terms of percentage of normal within the target area itself. An example is shown in Fig. 3. The principal feature of the distribution is a maximum near the center of the target area. Not all storms during the 1955–65 period have exhibited this pattern, but enough of them have done so to impress it on the total December–March rainfall accumulations for the decade. This is shown in Fig. 4. In those parts of the target area near the northern and eastern boundaries, the rainfall accumulations, expressed as percentages of the base-period averages, have not been much greater than those at the control stations. Therefore, the change in target-control relationship which accompanied the seeding program must have been brought about chiefly by the peak in the Morgan Hill area. As

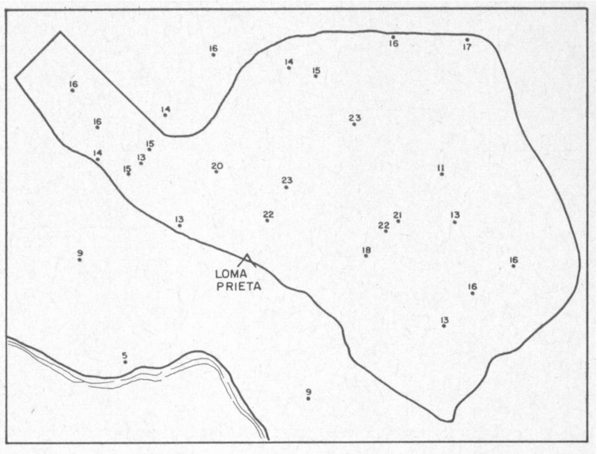

FIG. 3. Rainfall accumulations during storm of 24–26 February 1958 as percentage of December–March normal.

this feature occurs directly downwind of the most concentrated generator operations, it could be due to seeding. However, it is worth looking for natural causes which could have produced it.

The flow of stable air over a ridge is strongest through the passes, but with unstable air this effect is less pronounced. The Santa Cruz Mountains reach their highest elevation at Loma Prieta (Fig. 3), falling off to the northwest and southeast. Therefore, one would anticipate that rainfall accumulations during unstable storms, normalized by reference to seasonal totals involving both stable and unstable storms, would show maxima in the area around and immediately downwind of Loma Prieta, i.e., around Morgan Hill and Almaden Reservoir, although this would not necessarily lead to a favorable target-control relationship overall. There is a possibility that biases exist in favor of the target during unstable storms and against it during stable storms because of the inclusion of some coastal stations among the controls, whereas all the target stations are inland. Coastal rainfall maxima during stable storms have been reported and explained in qualitative terms by Bergeron (1949). An examination of those radiosonde observations at Oakland during 1958 and 1959 which coincided with the occurrence of rain in Santa Clara County suggested that a rainfall maximum near Morgan Hill and a favorable target-control relationship are associated with conditional instability extending from near the surface to above the freezing level. This does not prove that the observed anomaly and the favorable target-control relationship are entirely due to natural causes. An alternative hypothesis, to be explored below, is that seeding effectiveness is related to stability (Smith, 1962).

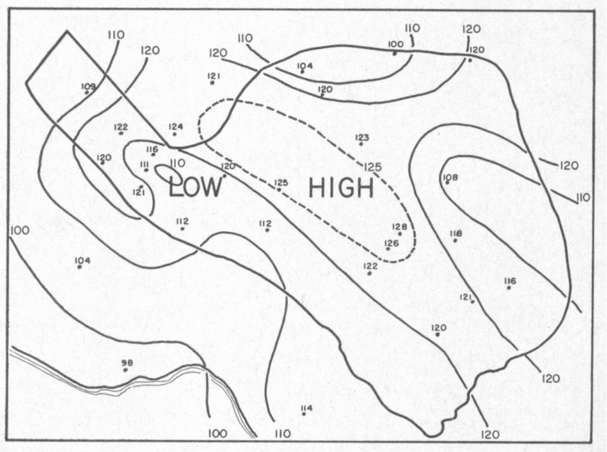

FIG. 4. Average rainfall accumulation as percentage of December-March normal for ten seeded seasons (1955–1965 inclusive except 1957).

Some authors, e.g., Neyman and Scott (1961), have advocated storm typing to account for variations in storm structure such as the stability variations noted here. However, as Todd (1960) has pointed out for Santa Barbara County, most storms cannot be classified as stable or unstable; convective instability and stratiform precipitation coexist within almost every one. There exists a continuum of possible situations; the markedly stable and unstable storms are thought of by the present authors as constituting the extremes of a single population rather than two separate populations. Autocorrelation in the storm series is not, of itself, sufficient justification for breaking a continuous population into sub-populations, i.e., types.

While agreeing with Thom (1957) in the rejection of storm typing, we nevertheless wish to inquire further into the possibility that a tendency toward unstable storms produced part, or all, of the apparent increases in target precipitation from 1954 to 1965. It does not appear feasible to gain more detailed information on such a hypothetical change by examining Oakland radiosonde data because of the way unstable periods are distributed within storms. A more promising approach is to examine the rainfall regime at the control stations, as unstable storms produce high rainfall rates at all target and control stations. Accordingly, we have compiled the distribution of daily rainfall accumulations at Ben Lomond, the control station showing the best correlation with the target, for the 10 seeded years and for the base period and plotted normalized cumulative distributions. The plotted data (Fig. 5) do not indicate any change in the rainfall regime. The authors conclude, therefore, that the persistent anomaly in normalized rainfall distribution within the target area during the 10 seeded years (as opposed to the extreme anomalies during certain storms) is not the result of increased instability.

4. Relationship of seeding effectiveness to instability

The results to this point lead us to conclude that rainfall in Santa Clara County has been increased by seeding. The fact that the increases appear to be concentrated 5 to 15 miles downwind of the generator sites in the Santa Cruz Mountains suggests that effects are most pronounced during periods of convective instability. With the freezing level typically 4000 ft above the crest and the winds at the freezing level blowing across the crest at 50 kt, seeding effects could not be felt so close to the generator sites if the silver iodide were carried upward by diffusion alone or if the precipitation particles were growing by sublimation, i.e., as snowflakes. However, application of Douglas' (1960) results on growth by accretion in cumuliform clouds shows that precipitation particles could form around the silver iodide crystals and fall this close to the generators in unstable situations. The fact that the apparent effects of seeding were near zero in the dry years of 1961 and 1964 (Fig. 2 and Table 2), which were characterized by weak, stable storms, is further evidence that detectable seeding effects are limited to periods of convective instability. The same conclusion has been reached by Elliott (1962) on the basis of a study using hourly precipitation rates.

Some further suggestive but admittedly inconclusive evidence on this point is given in Fig. 6, which shows the normalized cumulative distributions of rainfall in terms of daily rates for the base period and for the 10 seeded years at a target station (Almaden Reservoir). Because the method of operation, described above, could not lead to an increase in the number of rainy days, any increase in total rainfall must result in a shift of the plotted points to the right of where they would have fallen in the absence of seeding. Such a shift of the points for the 10 seeded years with respect to those for the base period is observed, but it applies only to days with rainfall amounts greater than 0.50 inch, that is, to days with some convective instability.

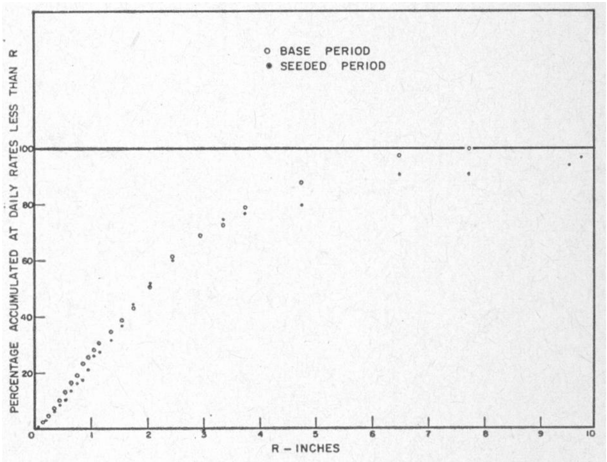

FIG. 5. Normalized cumulative rainfall distribution at Ben Lomond (a control station) during base period and during ten seeded seasons.

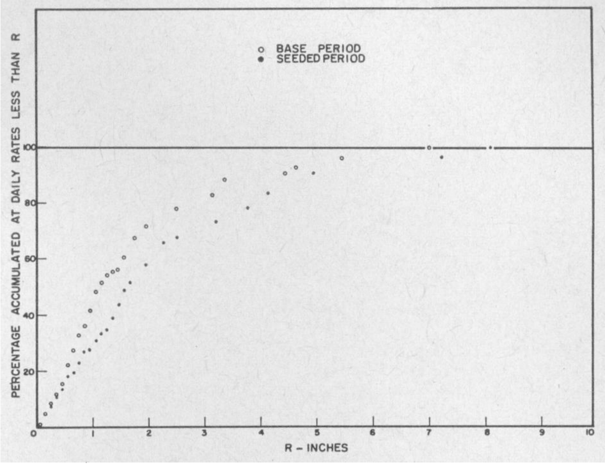

FIG. 6. Normalized cumulative rainfall distribution at Almaden (a target station) during the base period and during ten seeded seasons.

There is a plausible physical explanation for the apparent enhancement of seeding effectiveness in unstable situations. Regardless of whether silver iodide acts simply through the production of additional precipitation particles or through some dynamic effect, it can only be effective in the presence of supercooled water. In stable storms, natural seeding from the cirrus level can be operative down to the freezing level. Such seeding is sometimes very efficient in the Santa Clara area; pilots of the seeding aircraft sometimes report dry snow in those storms at temperatures between 0 and −10C. On the other hand, their reports of aircraft icing and hail in the convective cells show that relatively large quantities of supercooled water are present there; perhaps the updrafts themselves protect the supercooled water from the cirrus seeding.

Much work remains to be done before a complete picture of winter storms in the Santa Clara Valley is obtained. However, the money spent on seeding during the past eleven years has produced considerable meteorological knowledge as well as the additional rainwater which was the primary objective of the seeding program.

Acknowledgments. All control gages are operated by the U. S. Weather Bureau or by the San Francisco Water Department. The target records were obtained from the Weather Bureau, the Santa Clara Valley Water Conservation District, the San Jose Water Works, the San Francisco Water Department and from private sources.

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